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DIESEL COMBUSTION ANALYSIS
USING RAPID SAMPLING TECHNIQUES

FINAL REPORT

G.L. BORMAN, P.S. MYERS, O.A. UYEHARA

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U.S. ARMY RESEARCH OFFICE

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20. ABSTRACT CONTINUED

The purpose of the research was to obtain a better understanding of the fundamental processes which take place in a diesel cylinder during combustion. A single cylinder, open chamber engine with a special head designed to allow in-cylinder sampling was used for the research. Using a conventional injector, two kinds of sampling projects were carried out; timed sampling of small local samples using a probe and total cylinder sampling, achieved by suddenly expanding and transferring 80% of the cylinder content to a quench chamber. A third study used an electronic fuel injection system to study the effects of injection parameters on performance, heat release, ignition delay and exhaust emissions.

The total cylinder sampling method gave histories of total NO in the cylinder versus crankangle for various speeds, loads, EGR levels, injection timings, swirl levels and number of injector holes. The data show that NO has a rapid rise time of 17 to 25 crankdegrees and can overshoot the exhaust levels for heavier loads and advanced timing. The rate of change of total cylinder NO mass with crankangle was typically proportional to the exhaust NO level. Comparisons with a number of existing combustion models showed these models produced the correct history shapes, but did not reproduce absolute values very well.

Two differently designed sampling probes were used to obtain time and spaced resolved samples. The U.W. designed continuous-flow-probe was used to obtain the initial data and the GM designed intermittent probe was used for the second set of data. Comparisons of data from the two probe types were inconclusive. Chemical analysis of the samples was carried out for both unoxidized and oxidized filtered samples. This procedure allowed calculation of the fraction of injected fuel carbon mass that was collected as liquid or solid on the filter and also the H/C ratio of the gaseous sample. Tentative scenarios of the spray and combustion events with emphasis on swirl effects have been produced by study of the maps produced from these data.

Data taken with the electronic fuel injection system show that at high rates of injection the best results were obtained with low swirl and high injection pressure. Limiting the injection rate by reducing the number of holes was helpful, but the experiments were limited because the smallest hole size available is 0.0079 inch (0.2mm).



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THE PROBLEM STUDIED

The purpose of the research was to obtain diagnostic information on the in-cylinder combustion that take place in an open chamber diesel engine.

Because diesel combustion is very complex and heterogeneous, models have thus far tended to predict overall events without specific spatial resolution. Such models also contain many adjustable parameters, leading to questions concerning the extent to which the models represent physical reality. The research was intended to provide an experimental base for model evaluation and development in addition to providing a better understanding of the combustion phenomena.

Because combustion events take place in a very short time span (milliseconds) the experimental methods used were required to provide a high degree of time resolution. The use of optical methods to obtain local values of concentrations is very difficult in a diesel because of the high luminosity of the flames. Although such methods now show great promise, they were not readily available at the start of this research. The technique used in the present study was thus the much older method of time resolved sampling. Such sampling should ideally provide a means of removing a small sample of gas from the cylinder over a time interval short enough to resolve the combustion events. The probe should not disturb the cylinder gas flow or kinetics and should freeze the chemical reactions of the sample so that subsequent analysis will show the chemical composition of the gas at that location and time. Even if such an ideal probe could be produced it would not provide complete information since the motion of the gas is not resolved by the probe. The actual probes are of course not ideal; they do disturb the gas flow, they may only partially freeze the reactions in the sampled gas and the time resolution is only one or two milliseconds. Thus sampling probe data provides a somewhat blurred and distorted image of the combustion process (see Turns and Borman, 1980). In addition, the small samples taken from a given engine cycle are too small to be chemically analyzed with conventional instruments. Thus the samples from many cycles were combined so that the data represent cycle averaged values. This further blurs the picture because variations at a given point from cycle-to-cycle caused by turbulence are averaged out. Despite these limitations, sampling does provide a relatively simple and reliable means of combustion diagnostics. The sampling probe data gathered in this work thus do give insights into the mechanisms of the combustion processes. By comparing the analysis of the raw samples and samples after filtering and oxidation it is possible to make observations concerning the general kinetic nature of the reactions, the fuel air ratios of the combustion and the effects of such parameters as swirl on these events.

In theory, one could integrate the sampling probe data over the volume of cylinder to obtain the total cylinder mass of a particular species as a function of crankangle. Such data is needed for evaluating models because the models often predict only such total mass numbers. Because of the limited probe locations and the limited accuracy of the probe data it is unlikely that such integrations could provide reliable data. Thus a second sampling technique was used to obtain a nearly

total cylinder sample at a given instant. We have called this technique "dumping". The dumping method utilizes a special port in the cylinder head which connects the cylinder gas to a quench chamber. The port is closed on the cylinder gas side surface by a metal diaphragm until it is desired to "dump" the cylinder. At a given crankangle, the diaphragm is then cut and the cylinder contents rapidly expand into the quench chamber. On this sample cycle at the time of diaphragm cutting, the fuel injection is stopped and the engine valves are deactivated. The quench tank, after a dump, contains 80 to 90 percent of the cylinder gas. This gas was chemically analyzed to determine species such as H_2 , CO , CO_2 , O_2 , N_2 and NO_x . Because the ability of the dumping process to freeze such species as CO is questionable, the emphasis of the study was placed on the NO_x data. Nitrogen oxide reactions are relatively slow and post-flame, thus freezing them by dumping is almost certain. One should note that most diesel combustion models have also emphasized the prediction of NO because the NO kinetics are much better known than for other species. Thus dumping data provided a particularly good way to evaluate the models (Shahed, et al.).

Sampling and dumping data were obtained for changes in injection timing, number of nozzle holes and swirl ratio. However in order to understand the important role played by the injection process it is necessary to also change such injection characteristics as rate-of-injection and injection pressure. In order to extend the study to include these parameters an American Bosch "UFIS" (Universal Fuel Injection System) was obtained. This electronic fuel injection system provides means for fuel metering over a fairly wide range of rates and pressures. Inclusion of this injector in a special head thus allowed study of the effects of injection parameters on the combustion and emissions. In particular, emphasis was placed on obtaining ignition delay data.

EXPERIMENTAL APPARATUS

The experiments were all performed on a TACOM-Labeco single cylinder diesel engine. The original head of this engine has the injector axis located at an angle to the cylinder axis and has no room for insertion of a sampling probe into the combustion chamber bowl. Two differently designed special heads were thus fabricated and used in the research reported here. The first head was developed prior to the work reported here and was based on a I.H.C. four valve prototype head. This head was operated with only two valves using specially designed valve gear. The other two valve locations were modified to become instrumentation ports. A number of factors caused this first modified head to fall short of the research needs. Chief among these was the impossibility of adapting the head to utilize the American Bosch UFIS. This electronic injection system requires a much larger hole in the head than does the conventional Robert Bosch injector. Because utilization of the UFIS was an important aspect of the research, a new head was designed and fabricated under the contracts reported here. This head incorporated a number of desirable design features:

1. Provision for mounting either the conventional or the electronic fuel injector.
2. Injector at center of cylinder and mounted vertically so that it can be indexed when taking sampling probe data.
3. Intake valve with shroud so that swirl can be varied.
4. Large (1.5" diameter) instrumentation port in the head.
5. Valve "selectors" so that the valves may be deactivated upon command — this feature is used when taking dumping data.

In addition to the new head, the engine setup was provided with exhaust gas recirculation, heated and pressurized inlet air and a mini-dilution tunnel for particulate measurement. Additional instrumentation was also added to make possible measurement of water vapor concentration and hydrogen concentration in the probe or dumping samples.

During all but the last year of the reporting period, cylinder pressure data were recorded by use of a digital oscilloscope with disc storage. During the last year, the lab obtained a digitizer with computer memory storage and CRT display terminal. This system greatly increased the ability to record and analyze data.

Much of the sampling work involved development of techniques for analysis of the samples. A portion of the bag sample was filtered and dried before G.C. analysis. Another portion was diluted with oxygen and then catalytically oxidized to CO_2 , O_2 , N_2 and H_2O . Water was measured using a dew point hygrometer. The oxidized sample was then dried and analyzed with a G.C. A similar oxidation procedure had been followed by Rhee, in earlier work, but in the present work the analysis of the oxidized sample was extended to include the water and the unoxidized sample analysis was extended to include H_2 and CH_4 .

SUMMARY OF RESULTS

The results of the research fall into three parts; total cylinder sampling, spatially resolved sampling and injection parameter variations. Each part is discussed separately below with a final summary statement following these separate discussions.

TOTAL CYLINDER SAMPLING

Total cylinder samples were obtained by the dumping method. The method was used primarily to obtain histories of the total amount of NO in the cylinder as a function of crankangle. The data show that NO has a rapid rise time of 17 to 25 crankdegrees and can overshoot the exhaust levels for cases of heavier loads at advanced injection timing. Comparing the effects of parameters, the rate of NO was generally proportional to the exhaust NO level. An exception was the comparison between an eight-hole nozzle at low swirl and a four-hole nozzle at high swirl. The exhaust NO levels were about the same for these two cases, but the high swirl with the four-hole nozzle gave a much higher rate of NO formation at retarded timing than the low swirl with the eight-hole nozzle. At advanced timing the NO rates for both cases were much higher, in keeping with the much higher, but again essentially equal, exhaust values.

Again, the four-hole nozzle NO history gave a higher slope than the eight-hole nozzle history. A plot of total NO versus percent mass burned showed that at both timings the four-hole nozzle with high swirl gave much more NO at the 50% burned point than the eight-hole nozzle. The eight holes with high swirl gave about the same slope and same NO value at 50% burned as the eight holes with low swirl, but gave a lower rate during the last portion of burning and thus a lower exhaust value. One might venture that the four holes with high swirl gave a leaner burning mixture during early combustion than the eight holes with either low or high swirl. The high swirl did evidently affect the mixing during the later part of burning for the eight-hole nozzle. Of these various combinations at the retarded timing, the eight-hole nozzle with low swirl gave the best performance but also the highest exhaust NO.

Dumping analysis of the H_2 and CO content showed trends which seemed to be reasonable, but since these species may not be quenched by the dumping process these data are of questionable validity.

A comparison of some of the data with existing model calculations showed that the models tended to produce the correct NO history shapes and in most cases the correct trends with parameters. However, comparisons between models and the swirl parameter variations are still underway. Absolute values of exhaust levels were not as well reproduced by the models. Among the models tested the Cummins Model (Chiu, et al.) gave the best overall results.

SPATIALLY RESOLVED SAMPLING

The sampling method was originally conducted by use of a rotary probe developed at U.W. under a previous grant (Rhee, et al.). In this type of probe the cylinder gas flows continuously through a small hole in the probe tip. A tube located inside the probe rotates over the hole in the tip at a selected time diverting the flow into a collection volume. The sampling duration is about one millisecond. A study of engine sampling probe characteristics and the way they disturb the flow conducted by Turns at U.W. under a DOE contract later indicated that an intermittent, poppet type probe might give somewhat less distorted samples than the continuous flow rotary probe and thus better spatial resolution. Turns also predicted from theory that although the continuous flow sampling probe would give less quench bias, the effect of quench bias would be small for both types of probes. A further experimental investigation of these differences was conducted under the ARO grant by taking engine data with both probes and comparing the results. The results were inconclusive perhaps indicating the differences are small. The intermittent probe was judged more reliable, however, and thus it was used for the second round of data taking.

Sampling data were taken for a fixed engine condition of 1000 RPM, 0.6 equivalence ratio and 15° BTDC timing. Turbocharged conditions were simulated by holding the intake pressure at 0.145 MPa (21.3 psia) and 65.6°C (150°F). The swirl level was changed by use of the shrouded intake valve. Two settings were used corresponding to low (swirl ratio of about one) and high swirl (swirl ratio of about four). The eight-

hole nozzle was used for all tests. The sampling probe center was located radially inward 0.41 in. from the piston bowl rim and 0.25 in. down from the head surface. The injector was indexed so that sampling data was effectively taken along an arc with 1.34" radius and a 33° included angle. The probe locations relative to the spray centerline were; on the centerline, 11° to either side and 22° in the antiswirl direction.

Analysis of the data obtained from the unfiltered but oxidized and the filtered but unoxidized samples allowed calculation of the filtered-out moles of carbon per mole fuel. Also calculated was the H/C ratio of the sample gas phase; this quantity was found to correlate with local values of equivalence ratio calculated from the filtered, gas phase samples. Values of H and H/C for the filtered out material were calculated, but subsequent error analysis showed them to be unreliable.

Detailed maps of the computed and directly measured quantities were given in the published technical paper (Logan, et al.) and will not be reproduced here. Some general conclusions reached from these data are listed below for each of the two swirl rates.

Conclusions from low swirl data were:

1. Significant inhomogeneity exists at early crankangles. The equivalence ratio peak are broad at early crankangles with a narrow valley between the peaks. At later crankangles the valley grows in size with a decrease in the height of the peaks. The valley equivalence ratio is relatively constant growing from 0.5 at early crankangles to 0.65 at 30°ATDC. The entire equivalence ratio map rotates in the direction of the swirl at about one degree per crankangle degree.
2. Intermediate gaseous species which are formed in the high equivalence ratio regions appear to be convected into the low equivalence ratio valley where they survive for sometime. It is speculated that the valley regions are lower in temperature and thus the reaction rates are lower there.
3. At early crankangles oxidation of hydrogen intermediates to H_2O is preferred over the oxidation of carbon intermediates to CO_2 .

Conclusions from the high swirl data were:

1. Carbon residual peaks were found along the spray center line and showed no deflection as might be caused by swirl. Such carbon residual may indicate a core of undeflected liquid fuel. In contrast, the gaseous sample equivalence ratios were very uniform and low until quite late crankangles. At 30°ATDC and later crankangles, islands of higher equivalence ratios appeared to the downstream side of the spray centerline.
2. Values of CO and H_2 were much lower than for the low swirl case and showed the same trends as the equivalence ratio, again indicating lean homogeneous conditions at early crankangles.
3. At early crankangles, the CO_2 concentration is very low with islands of CO_2 building up between the spray plumes. This may indicate rapid oxidation of lean gaseous mixtures swept out of the spray by the swirl.

4. Interpretation of the data for high swirl is inconclusive. One interpretation is that the swirl greatly inhibited fuel penetration to the probe position. Such an interpretation does not, however, agree with other observed spray behavior which would indicate the spray core is only slightly bent and inhibited by the swirl while smaller droplets and vapor are swept sidewise out of the spray plume. Such an alternative explanation of the data could hold if the probe were less efficient in collecting liquid fuel under high swirl conditions.

INJECTION PARAMETER VARIATIONS

The study of injection parameter effects on combustion was undertaken to try to isolate the injection effects from other parameters and to more clearly delineate the effects of injector pressure and rate on ignition delay and particulates. To reduce secondary effects, the data were taken by adjusting the intake pressure and temperature to always give the same temperature and pressure at the start of injection. As in the case of the sampling data, the two conditions of high and low swirl were studied. Data were limited, at the onset, by the minimum hole size tips available for the UFIS. Rates of injection for both the eight- and six-hole nozzle tips with 0.0096 holes are very high. Data from the smallest hole diameter (.0079 inch) nozzle has been limited due to malfunction of one of the nozzles. It also appears that accurate metering of the fuel is not possible because of internal leakage within our nozzle. The conclusions that can be drawn from the data are thus quite limited. For the high swirl, the smoke number and particulate mass both decreased dramatically with increasing rail pressure, however both the NO_x and unburned hydrocarbons increased. Ignition delay decreased with rail pressure for both nozzles but appeared to reach a minimum and then increase again for the six-hole nozzle. This later observation requires additional verification.

The low swirl case data were generally less sensitive to rail pressure. Smoke and particulates were much lower than for the high swirl and were reduced by increasing rail pressure. Exhaust hydrocarbon and NO_x levels did not change much with rail pressure. Ignition delay was somewhat smaller than for the high swirl and decreased with increasing rail pressure. The data indicate that low swirl is more desirable than high swirl for the conditions tested. Reduction in the rate of injection by decreasing the hole size appears to be desirable.

OVERVIEW

The process of unraveling the complex maze of phenomena that take place in diesel combustion will not be accomplished with any one grant or any one technique. Thus the methods and results reported here are simply one step toward a better understanding of the phenomena. Both the sampling probes and dumping technique provided useful, but incomplete and imprecise, information.

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